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Identifying hotspots and representative monitoring area of groundwater changes with time stability analysis

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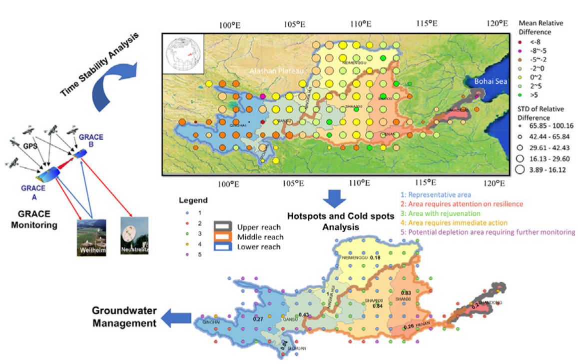
HIGHLIGHTS

- Time stability of GRACE data was used for the 1st time in groundwater (GW) studies.
- Spatio-temporal dynamics of GW table were quantified in Yellow River Basin, China.
- Hotspots, coldspots and representative areas of GW dynamics were identified.
- Clustered areas were identified for various management needs.
- Potential modifications in GW management within the basin were suggested.

GRAPHICAL ABSTRACT



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ABSTRACT

Groundwater is a most accessible freshwater resource for human beings, and it is increasingly important as an alternative to surface water under the threat of climate change. However, its complex spatio-temporal dynamic remains unattended from management perspective. Past studies on groundwater management were stalled by a relative dearth of high-quality data and a lack of synthetic analysis on both spatial and temporal information. Thanks to NASA's launch of Gravity Recovery and Climate Experiment (GRACE) satellite mission, our study has solved these two problems by innovatively applying time stability analysis to GRACE-based groundwater data. Taking the Yellow River Basin (YRB) as an example, we employed GRACE satellite data to obtain monthly changes of groundwater tables from Jan. 2003 to Dec. 2016 in 1.0-degree grid of spatial resolution. Then we identified hotspots (which indicated severe groundwater declines and fluctuations over time) and representative monitoring areas (which stably represented the spatial average over time) using time stability analysis. Time stability employs multiple coefficients to identify the spatial relations between local variables and global variables overtime, thus showing the overall effect of spatial-wise and temporal-wise factors but never used in groundwater studies before. Based on this innovative method, we further identified management categories across the YRB using multivariate cluster analysis. As a result, the YRB has been divided into five zones for different management strategies. We identified the hotspots in west-most and east-most areas of the YRB, where we suggest a strengthened groundwater protections and risk response system. The northern part of the middle reach in the YRB was also identified as the representative monitoring areas. With these knowledge, decision-makers can

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have a clearer regional plan for groundwater protection, monitoring, and risk response system. This new method enables a quick decision on the prioritized areas for different groundwater management strategies while not losing the scope of spatio-temporal heterogeneity.

1. Introduction

Groundwater is an indispensable water resource to sustain food security and increase ecosystem resilience (UNESCO, 2004; Whymap, 2008; USGS, 2016; Rodell et al., 2018). However, the pressures from climate change and increasing population have profoundly changed groundwater reserves over time (Hanjra and Qureshi, 2010). When groundwater is depleting, cities will have much less capacity in dealing with extreme climate events and will have more serious and irreversible strain on water supply (Konikow and Kendy, 2005). Therefore, it is imperative to protect and manage groundwater in a sustainable manner. Many researchers have emphasized the importance of the knowledge and information concerning groundwater resources for water management (Villholth, 2006; Ahmadi and Sedghamiz, 2007; Xiao et al., 2016). Identifying signs of groundwater depletion (hotspots) and flooding (coldspots) is especially necessary for managers to take proactive action to evade potential water crises. With emerging water scarcity problems around the world, more water users rely more on groundwater resources but seldom have realized its importance for sustaining future generations (Watkins, 2006; Hanjra and Qureshi, 2010; Hoekstra and Mekonnen, 2011). There is an urgent need to obtain a complete and sufficient understanding of the groundwater changing trend at regional scale to construct a sustainable groundwater supply system.

Previous analyses of groundwater changes focused separately on temporal and spatial scale but have rarely synergistically examined changes across both time and space (Ahmadi and Sedghamiz, 2007; Xiao et al., 2016). For example, Cameron and Hunter (2002) used the geostatistical temporal-spatial algorithm to optimize the long-term monitoring networks. However, they processed the spatial and temporal information separately, and the method was only used for redundant points of the groundwater quality. Theodossiou and Latinopoulos (2006) analyzed the spatial variation using kriging method, however, missed the temporal information, thus being insufficient for crafting management strategies for the future. Xiao et al. (2016) separately analyzed the spatial variabilities and temporal changes of groundwater level in Beijing piedmont from 2001 to 2013, however, they failed to interpret the groundwater situation synergistically. In reality, the factors in spatial and temporal scales are working together and interconnected to contribute to the changes of groundwater. Accurately identifying hotspots of groundwater depletion and increase requires information across both time and space simultaneously.

Time stability analysis has been widely used in soil moisture studies to examine the time invariant association between spatial location and classical statistical parametric values of soil water content (Vachaud et al., 1985; Biswas and Si, 2011; Hu et al., 2014). Many studies observed that, at certain area, the spatial pattern of soil water content remain stable with time at a certain probability (Comegna and Basile, 1994; Brocca et al., 2009). Moreover, the area with this characteristic of time persistence in spatial pattern can be used as a representative monitoring area for the spatial average of a given area (Grayson and Western, 1998; Hu et al., 2013). Therefore, the time stability analysis shows promise to improve understanding on the changes of soil moisture in a spatio-temporal explicit way.

There are no studies that used the time stability analysis for the spatio-temporal analysis of groundwater. One main reason is the difficulty of getting satisfying datasets for the trend analysis in both spatial and temporal scale. With recently available dataset of groundwater changes from GRACE projects, it is now possible to unveil the mask of groundwater in a spatio-temporal explicit manner (Bhanja et al., 2016; Rodell et al., 2018). Therefore, for the first time, we adopt the time stability analysis coupled with multivariate cluster analysis to provide effective support for groundwater management.

The objective of this study is to examine spatio-temporal changes of groundwater in the Yellow River basin (YRB) to identify representative areas for monitoring and hotspots of depletion or increase that require further attention. In this study, we innovatively used the time stability analysis and cluster analysis to synergistically analyze the spatio-temporal changes of groundwater in the YRB and have accordingly provided suggestions for the management plan of groundwater reservation.

2. Material and methods

2.1. The Yellow River Basin

The YRB (elevation ranging between 0 and 4800 m), located in the north of China, is one of the largest river basins in the world, with an estimated recharge area of 795,000 km^2 (Fig. 1). From the upstream of the Yellow River, where the Qinghai-Tibet Plateau (Point A in the Fig. 1) locates, the river basin's elevation generally decreases until the river mouth in the East (D) (Yu, 2002; Liu and Di, 2007). Hekou County (B) and Zhenzhou City (C) are the two separated points which divide the river to three components, forming three reaches from high west to low east. Because of the high disparities in altitude from the upper reach to middle reach, the middle reach suffers from high water erosion with infertile lands in the loess and ordos plateau. The lower reach consists of alluvial plains, which are good for growing crops, and therefore features high population density and urban areas compared with reaches upstream. However, lower reach suffers from flood events the most. Accordingly, the water management in the YRB is traditionally focused on flood control and irrigation management (Giordano, 2004).

There are nine provinces along the river: Qinghai, Sichuan, Gansu, Ningxia Hui, Shaanxi, Neimenggu, Shanxi, Henan, and Shandong (Fig. 1). The river currently nourishes >120 million people (12% of China's population), waters >200,000 km^2 arable land (15% of China's farmland), generates nearly 8 trillion yuan per year (14% of China's GDP), and is an important cultural and historical icon (Hays, 2009). But under the pressure of climate change, increasing water demand and the growing economy, the water scarcity problem has become the pioritized issue for the recent decade (Giordano, 2004).

2.2. Hydrogeological background of the YRB

With close interaction to the Yellow River, certain types of groundwater in the YRB have typical distributions consistent with its surface water systems. Loose sediment rock type pore water is most widely distributed in the YRB and is important water supply. Frozen-layer water mainly lies in the upper stream, the Qinghai Tibet Plateau area, flowing above or under the permafrost layer. Clastic rock type fissure and pore water is scattered in mountain piedmonts and artesian basins in the middle stream, like Ordos Plateau in Neimenggu, and Weihe Catchment in Shaanxi. Carbonate rock type fissure and pore water including karst waters mainly occur in lower stream, e.g. Lvliang Mountains in Shanxi and Liupan Mountain in Ningxia.

Because of the various landforms and complex lithology in the YRB, groundwater systems in the YRB are also intricate. Cui et al. (2004)

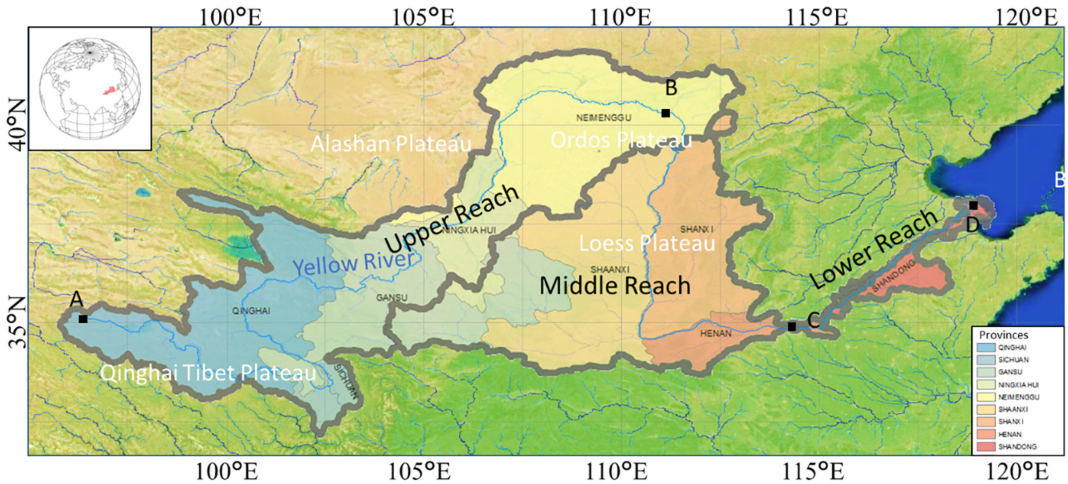

Fig. 1. Yellow River Basin, the study area. The bold lines delineate three reaches (upper, middle and lower reach). The colored polygons represent nine provinces in the YRB. The blue curves represent the flow accumulation across the basin. The main flow path of the Yellow River is bolded by a continuous blue curve from Qinghai-Tibet Plateau passing Alashan Plateau, Ordos Plateau and Loess Plateau, then extending towards Bohai Sea. Point A, B, C and D are the key points of the Yellow River: AB is the upstream, BC is the middle stream, and CD is the downstream.

divided the YRB into 9 groundwater systems according to surface watersheds while Eryong et al. (2009) partitioned 12 groundwater systems based on hydrogeological conditions and characteristics of recharge-runoff-discharge of groundwater. In spite of different classifications, it is commonly recognized that the main recharge resources of groundwater are precipitation, surface water (irrigation, and river water infiltration) and lateral bedrock regions, and the main discharge channels are through evapotranspiration, human abstraction, river runoff and springs (Xu et al., 2002; Eryong et al., 2009; Han et al., 2009; Xu et al., 2010; Xu et al., 2011).

Although previous studies made efforts in identifying different groundwater zones in the YRB and their recharge-discharge systems, it is still hard to draft targeted and effective groundwater plan without closer look at the changes of groundwater storage. Nevertheless, the geology and the system mediated changes will be rather spatially constant, and the temporal change would be dictated by the external influences.

2.3. Data sources and data analysis

We used datasets obtained from a remote sensing data product and a data assimilation system to calculate monthly groundwater changes in the YRB for 2003–2016 at the spatial resolution of $1° \times 1°$. The terrestrial water storage was obtained through the Gravity Recovery and Climate Experiment mission (GRACE) (http://grace.jpl.nasa.gov) and the surface water equivalence, soil moisture and snow water equivalence were obtained from the Global Land Data Assimilation System (GLDAS) (https://disc.gsfc.nasa.gov). Groundwater was calculated based on the principle of mass conservation, by subtracting terrestrial water storage with the rest of abovementioned variables. The calculated groundwater changes are the groundwater levels compared with the monthly average from Jan. 2004 to Dec. 2009. For details of data processing, please refer to Lin et al. (2019).

We adopted time stability analysis to examine the spatio-temporal changes of groundwater levels. Different indices have been used to measure time stability in multiple scales (Jacobs, 2004; Guber et al., 2008; Schneider et al., 2008). We used the Mean Relative Difference (MRD) and the Standard Deviation of the Relative Difference (SDRD) to synergistically identifying spatial and temporal information in each grid (Tallon, 2004; Brocca et al., 2009). This has previously been used in soil moisture studies to identify representative locations for regional monitoring (Brocca et al., 2009; Cosh et al., 2008). We innovatively used it here for groundwater changes in order to find both the time stable and unstable locations in the YRB. Mean Relative Differences were calculated as:

$$MRD^i = \frac{1}{k}\sum_{j=1}^{k}\left(GW_j^i - {}^s\overline{GW_j}\right)/{}^s\overline{GW_j};$$

where

$${}^s\overline{GW_j} = \frac{1}{n}\sum_{i=1}^{n} GW_j^i.$$

GW_j^i is the groundwater change in ith grid and jth month;

${}^s\overline{GW_j}$ is the spatial average of the groundwater values in the YRB in jth month; n is the total number of grids in the YRB and k is the total number of months during the study period. MRD^i is actually the temporal mean during 2003–2016 of the relative difference of each grid compared with the spatial average of the grids in the YRB.

The Standard Deviation of the Relative Difference (SDRD) was calculated as:

$$SDRD^i = \sqrt{\frac{1}{k-1}\sum_{j=1}^{k}\left(\delta_j^i - {}^t\overline{\delta^i}\right)^2};$$

where

$$\delta_j^i = \left(GW_j^i - {}^s\overline{GW_j}\right)/{}^s\overline{GW_j};$$

$${}^t\overline{\delta^i} = \frac{1}{k}\sum_{j=1}^{k}\delta_j^i.$$

δ_j^i is the relative difference of groundwater change in ith grid compared with the spatial average of the YRB in jth month;

${}^t\overline{\delta^i}$ is the temporal average of the spatial relative difference for ith grid;

$SDRD^i$ is the sample standard deviation during 2003–2016 of the relative difference of groundwater change in ith grid compared with the spatial average of the YRB. In the two indices, s and t were used to differentiate spatial and temporal average. With these two indices, we could synergistically measure the spatial and temporal variability of each grid in a more explicit way.

Based on the MRD and SDRD values, we used the multivariate cluster analysis in ArcGIS to identify the places with time stable and unstable characteristics. The grids with minimal MRD and SDRD were defined as representative area for monitoring. Contrarily, the grids with very high absolute values of MRD and SDRD should be considered with caution. After multiple trials of the grouping strategy, we categorized the features of different grids into five groups:

Group 1 **Representative area**: the grids with minimum MRD and SDRD. This area has minimum groundwater changes and minimum groundwater fluctuations.

Group 2 **Area requires attention on resilience**: the grids with low negative value of MRD but very high SDRD. This area shows minor groundwater decrease, but with high fluctuations.

Group 3 **Area with rejuvenation**: the grids with high positive value of MRD and medium SDRD. The area shows the increase of groundwater and medium fluctuations.

Group 4 **Area requires immediate action**: the grids with very high negative value of MRD and very high SDRD. This area displays very severe groundwater decreases and very high fluctuations.

Group 5 **Potential depletion area that require further monitoring**: the grids with medium negative value of MRD and medium SDRD. This area displays medium groundwater decrease and with medium fluctuation.The detailed interpretation and respective suggestions for management will be explained in result and discussion.

3. Results

We mapped out the time-invariant spatial pattern of groundwater distribution across the YRB (Fig. 2). We then divided the YRB into five management zones (Fig. 3) according to their groundwater situations affected by both spatial and temporal drivers manifested by the values in the MRD and SDRD (Fig. 4).

Fig. 2 displays the general spatial relations of the groundwater tables with spatial average in the YRB over the past 14 years (2003–2016). Grids in the middle of the YRB (the eastern part of the upper reach and the western part of the middle reach) have MRDs closing to zero, which indicate that, despite variances of the spatial average over time, the groundwater tables in these places tend to be equal to the spatial average of the YRB. In the outskirt of the upper reach and the west of the middle reach, we found low SDRDs, which indicate that, despite high variances of the spatial average over time, the relations between groundwater tables in these grids and the spatial average of the YRB remain stable. Combining the two indices together, the north of Ningxia and the west of Neimenggu have both close-to-zero MRDs and low SDRDs (Fig. 2), therefore have a stable representation to the spatial average of the YRB. Accordingly, they were defined as representative monitoring areas which could be used to monitor the abnormal temporal changes of the whole YRB.

Fig. 4 shows the statistics of two indices for the categorized five groups. Both MRD ($R^2 = 0.82$) and SDRD ($R^2 = 0.80$) are effective in defining the five categories. The global mean of the MRD in the YRB from 2003 to 2016 is 0, and the global standard deviation of the MRD is 3.58. The global mean of the SDRD is 31.41 and the global standard deviation of the SDRD is 18.14.

Group 1 has similar mean (0.60) of MRD as the global mean of the MRD and has relatively smaller range of values (−1.85–3.15) than the global MRD. This, in another way, proves the representativeness of the groundwater tables in this area for the spatial average of the YRB. This group has smaller mean (14.89) and standard deviation (6.83) of SDRD than the global SDRD which indicates its stableness and reliance as a representative area for the YRB (Fig. 4). The mean of MRD in the Group 2 is −2.4, which means that the groundwater tables in this area were generally lower than the spatial average but were still in the normal range (within the lower quartile of the global MRD). However, its mean of SDRD is higher than the global mean of SDRD (52.54 > 31.41), which indicates that the differences between the groundwater tables in this area and the spatial average of the YRB varied considerably over time. Therefore, despite that this area generally had no severe groundwater declines, it had less stable recharge-discharge system whose resilience should be taken with caution. Group 3 has a higher mean of MRD (3.98) than the global mean of the MRD. And the grid with largest increase of groundwater table (MRD = 7.58) locates in this area (Fig. 4). Group 3's mean of SDRD (34.08) is close to the global SDRD which implies that the variances in this group were driven by similar forces as in the whole YRB. Altogether, this area showed normal fluctuations of groundwater table and had relatively higher water table than the spatial average. So, the groundwater reserve in this area is gaining surplus. Group 4 (hotspots: the area with severe groundwater declines which requires immediate action) not only showed most severe declines compared with the spatial average (mean of the MRD = -8.81) but also had abnormal fluctuations of the differences over time: Its mean of the SDRD is 81.02, which is far higher than the higher whisker of the global SDRD (Fig. 4). Let it alone its larger standard deviations for both MRD and SDRD than other four groups. It suggests that this area not only had severe groundwater decrease, but also

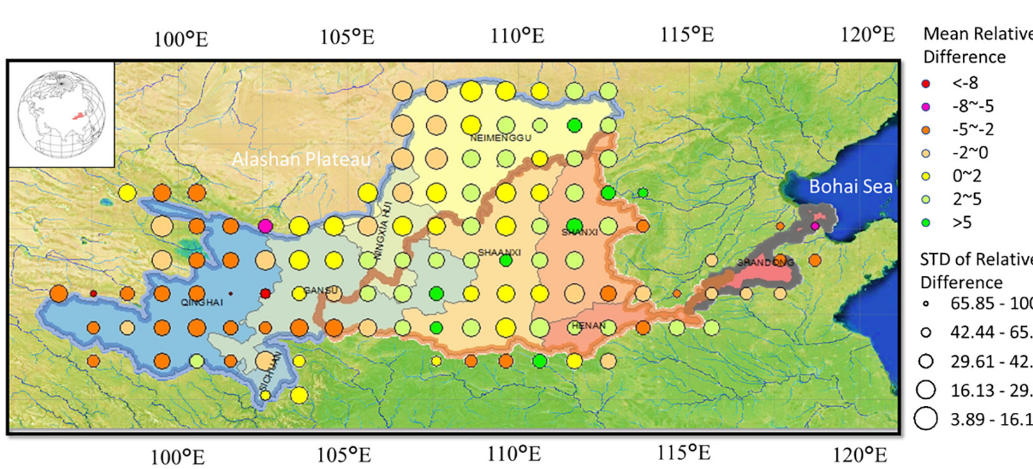

Fig. 2. Representative area for groundwater changes. The color of the circle represents different ranges of values for mean relative difference. The yellow and light orange colors are the target area where mean relative difference is relatively small (−2–2). The size of the circle represents different ranges of values for standard deviation of the relative difference, which is inversely proportional to the value of size. The largest size of circle is the target area where standard deviation is the smallest. The background map is the provincial map and topology map with stream flows.

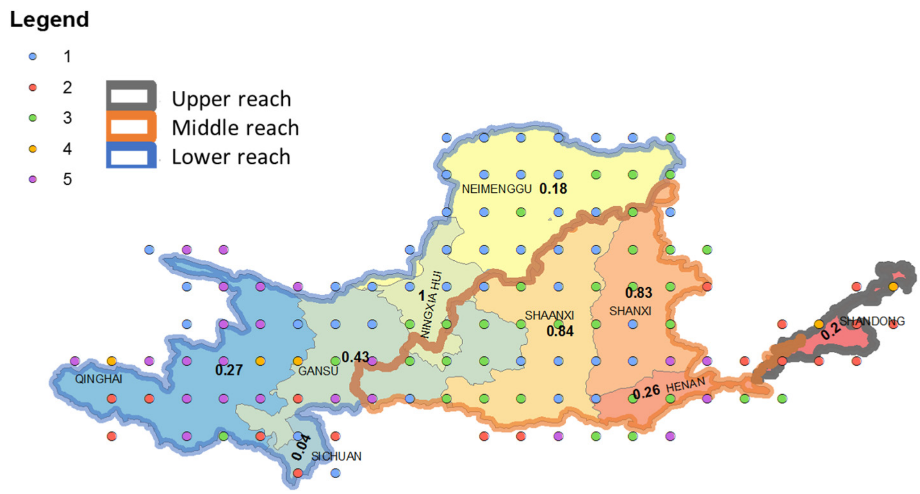

Fig. 3. Hot spots and cold spots areas of groundwater changes in the YRB 2003–2016. The colored circles represent five different groups that we identified through multivariate cluster analysis. Group 1: Representative area; Group 2: Area requires attention on resilience; Group 3: Area with rejuvenation; Group 4: Area requires immediate action; Group 5: Potential depletion area that require further monitoring. The colored boundaries represent the three reaches of the Yellow River. The colored polygons represent different provinces in the YRB, and the number in each province represents the percentage of the polygon in the total area of the province. For example, in Shanxi, 83% of the area is within the boundary of the YRB which is shown here while in Ningxia, 100% of the area is within the boundary of the YRB.

had very unpredictable fluctuations in both time and space. Group 5 has relatively stable relations with the spatial average (mean of SDRD = 31.0528) but has the second lowest mean of MRD among the five categories (mean of MRD = -3.2144). It suggests that this area kept having lower groundwater tables than the spatial average over time. This area may have less tendency to come across abrupt changes of groundwater table in the future, but its current low status in groundwater reserve should be monitored closely in case the water levels go under the acceptable threshold.

The Fig. 3 mapped out the geographical distributions of these five groups. The representative monitoring areas (Group 1) locate in the north of Ningxia and the west of Neimenggu as well as some scattered grids in the south of Shaanxi and Shanxi. The consistency of the Group 1 identified by the cluster analysis (Fig. 3) with the representative monitoring areas identified by time stability analysis (Fig. 2) mutually proved the methods' validity in identifying the area that could represent spatial average of the YRB over time. The areas that require attention on resilience (Group 2) locate in the lower reach around Shandong and in the tip of the upper reach. Their relations to spatial average varied a lot in time and space (Fig. 3). So, the resilience of the ecosystem and society in these regions is important to be strengthened to prepare for the abrupt changes of the groundwater table. The areas that showed the signs of rejuvenation (Group 3) are mainly in the middle reach, including the east of Gansu and the north of Shanxi. They showed most

Mean Relative Difference: R^2 = 0.82

Group	Mean	Std. Dev.	Min	Max	Share
1	0.6014	1.3192	-1.8541	3.1548	0.2450
2	-2.4099	1.6899	-4.7655	0.5950	0.2621
3	3.9846	1.3987	0.9909	7.5793	0.3222
4	-8.8055	3.3057	-12.8693	-4.8035	0.3944
5	-3.2144	1.3616	-6.9115	-0.6578	0.3058
Total	0.0000	3.5787	-12.8693	7.5793	1.0000

Stdev of Relative Difference: R^2 = 0.80

Group	Mean	Std. Dev.	Min	Max	Share
1	14.8869	6.8372	3.8965	28.8012	0.2587
2	52.5384	6.7354	42.4488	65.8565	0.2432
3	34.0840	9.1985	22.3783	59.6265	0.3870
4	81.0200	15.6499	58.4049	100.1510	0.4337
5	31.0528	7.2505	19.1178	41.5697	0.2333
Total	31.4146	18.1376	3.8965	100.1510	1.0000

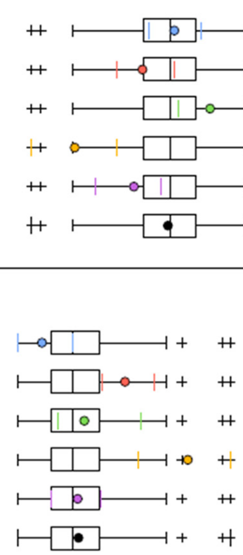

Fig. 4. Variable-wise summary of the multivariate cluster analysis for groundwater changes in the YRB (2003–2016). Different colors represent different group values. In each variable (the mean relative difference and standard deviation of the relative difference), the list shows its group statistics. R^2 indicates how effective the variables are in dividing the groups. The higher value represents higher effectiveness. The box plots on the right indicate the value range of the variable each group represents. The black box plots are the global statistics (including global lower whisker, global lower quartile, global median, global upper quartile, global higher whisker). The "+" represents the outliers which are the values away from the mean by 1.5 times larger than the standard deviation. The colored box plots are the group statistics (including group min, group mean, and group max).

obvious increase of groundwater levels therefore were identified as cold spots. The areas that require immediate action (Group 4), which displayed severe groundwater decreases, can be found in the origin of the Yellow River and at its river mouth (Fig. 3). They are also called hotspots that should be the focus of the groundwater management in the YRB. The areas that require further monitoring (Group 5) because they show potential depletions, are the source region of the YRB and the connection part of the middle and lower reaches, where there regularly showed signs of medium groundwater decrease over time (Fig. 3). Although these areas have less severe situations in terms of groundwater resource than the Group 4, they still need close monitoring in order to evade irreversible depletion.

4. Discussion

In 2002, NASA launched the twin-satellite to measure the gravity anomalies of the Earth. Groundwater study has since opened a new way to record water table trend in the globe at a relatively fine resolution (Richey et al., 2015). This breakthrough makes many other previously inapplicable methods become available for the hydrogeology study. Time stability analysis is one of them. While it was commonly used in soil water content analysis (Brocca et al., 2009; Biswas and Si, 2011; Hu et al., 2013), it had not yet been employed in groundwater studies before our research. For the first time, we innovatively explored the time stability analysis in this study to synergistically measure the spatial and temporal information of the groundwater changes.

We identified the representative area of the YRB which could be used to overall monitor the temporal trend of the basin (Fig. 2). They are the north of Ningxia and the west of Neimenggu which are relatively arid area across the basin, thus having relatively stable manifestations of water distribution over time. This result is consistent with the exploration of time stability in the soil water content studies by Hu et al. (2010) where drier locations have stronger time stability.

Despite the conceptual validity that measuring the representative area can capture the general trend of the whole basin over time, groundwater in the point scale may vary significantly due to different geological structures and various recharge-discharge systems. The more meaningful use of this method for groundwater study is to identify problematic areas. Here we further employed the indices of time stability analysis to identify clusters for management. The grids in Group 4 are the places require immediate actions (Fig. 3). It includes the source region of the Yellow River in the Qinghai province, and the river mouth in the east of the Shandong province (Fig. 4). The significant groundwater decrease in the source region indicates the potential glacier retreat in the Qinghai Tibet Plateau (Deng and Zhang, 2018) while the decrease in the river mouth may result from the increasing water demand with soaring population (Zhang et al., 2011).

Apart from the most problematic areas, other groups identified through the multivariate cluster analysis (Fig. 3) implicate different strategies in groundwater management. For example, the areas that requires attention on resilience (Group 2) mainly locate near the boundary of the YRB (Sichuan province, and the lower stream in Shandong Province). It implicates abrupt water interactions over the study period. These abrupt changes of water influx and outflow may partially result from the soil type (Zhu et al., 2010). A higher hydraulic conductivity of the aquifers (e.g. sand and gravel) with a low permeable basement (e.g. lacustrine deposit) and a continuing slope can lead to a quickly recharged or discharged groundwater system (Eryong et al., 2009). In the lower stream, the raised water bed is one of the main recharge of the aquifers (Han et al., 2009). The change of flood and dry season may also be a reason of the fluctuations. Moreover, these frequent fluctuations of groundwater levels may indicate a less stable and resilient ecological environment, which if extreme events arrive, may lead to considerable damage, like groundwater flooding, dry wells, and even land subsidence (Konikow and Kendy, 2005; Macdonald et al., 2008; Scanlon et al., 2012). Considering the increasing threat from the climate change (Famiglietti, 2014; Hanjra and Qureshi, 2010), it is suggested to strengthen its mechanism of environmental response (e.g. reservoir and flood control system) in the area so as to increase its capacity in withholding abrupt large amount of water inflow and surviving in the drought times.

The area with rejuvenation (Group 3) was mainly found in the middle reach which indicates general increases of groundwater levels in these regions (Gansu, Shaanxi and Shanxi). It might indicate the reduced discharge and/or the increased recharge. For example, Han (2003) listed several artificial recharge schemes conducted in China including surface-spreading system and deep well injection. Cong et al. (2009) suggested that artificial water consumption was the main cause of the drying up of the Yellow River after 1950s. And they indicated that a better situation of Yellow River in the 21st century was due to the enhanced management of the water resources. However, we should take caution in interpreting these signs of rejuvenation. It doesn't necessarily mean the freshwater resource here is free of concerns and that the water management is always on the right track. According to local news and related literature, it is suspected that there are increasing human injection of groundwater under the imbalanced rigor of law between the surface water and groundwater. That is to say, the monitoring system in groundwater on both quality and quantity is incomplete, thus having less restriction to industries than the surface water. While the wastewater effluent to surface water will be charged with high fees if not being treated, it is hard to detect the discharge of untreated sewage to the wells. To reduce the cost in water disposal, some companies will illegally inject the untreated sewage into the aquifers without water treatment (Keranen et al., 2014; Yin et al., 2016). In this case, the water quality of the groundwater may be of a concern, and an improved inspection system on the sewage to wells should be installed. Also, current water-saving constructions may have nonlinear impacts on groundwater storage changes. For example, Xu et al. (2010) testified that the groundwater storage will be reduced (water table lowered by 0.28–0.48 m) with the water-saving constructions in Hetao Basin. However, later on, they use MODFLOW and GIS to refute their previous results, announcing that water-saving constructions could save groundwater by reducing evaporation (Xu et al., 2011). Their change of results may at least demonstrate that the connections between groundwater and water-saving practices are complex and may be dynamic.

The result of multivariate cluster analysis provides one way of the categorization which we think is most meaningful. However, it is also possible to divide the YRB into groups based on other categorization that may be more practical for decision-making. When using this method to other areas, researchers are suggested trying different numbers of grouping for multiple times to find the most effective way for the specific questions. In this study, we have also used three groups to identify the clusters. The clustering is very consistent with the reach's divisions, however, may have less potential than the five-group clusters for effective management (Fig. 5).

Also, our limited timeframe of study (14 years from 2003 to 2016) may not be sufficient to capture long-term fluctuations of groundwater which are usually the cases for deeper aquifers. As GRACE data accumulated over time, we expect to obtain longer time series of groundwater recharge data to capture changes influenced by land cover changes and climate, thus serving for long-term water plan.

Despite the uncertainty in defining the clusters and limited timeframe, both the time stability analysis and cluster analysis in this study succeeded in displaying the spatial-temporal information in a more explicit way, thus providing clearer instructions for groundwater management (Chinnasamy et al., 2015). Our method can be adopted in water management in other regions, and we suggested combining obtained results with groundwater quality measurements for the final decision-making (Vousoughi et al., 2013).

With an increasing stress in the freshwater availability under exploding population and unpredictable climate change (Rodell et al., 2018), groundwater will play an increasingly important role as a natural

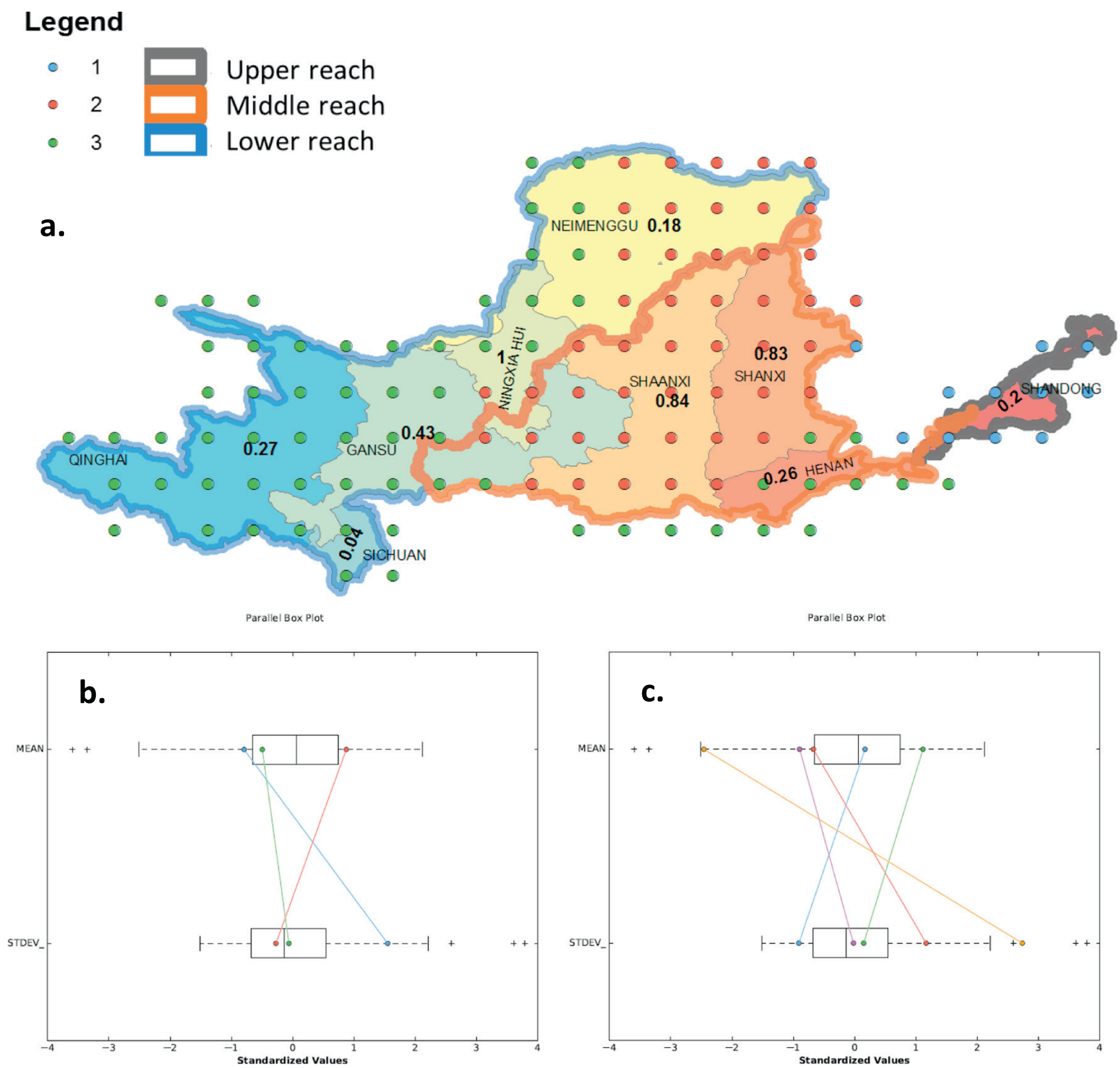

Fig. 5. The result comparison between different clustering strategies. a. The cluster map of three-cluster analysis for MRD and SDRD of groundwater changes in the YRB during 2003–2016. The left box plot (b.) shows the value distribution of each group compared with global statistics in the three-cluster analysis while the right box plot (c.) is for the five-cluster analysis (also see Fig. 3 for the cluster map of the five-cluster analysis). The black box plots are the global statistics (including global lower whisker, global lower quartile, global median, global upper quartile, global higher whisker). The "+" represents the outliers which are the values away from the mean by 1.5 times larger than the standard deviation. The colored dots in the two box plots indicate the median of the group values for the two variables. While the five-cluster analysis identified the extreme high negative value of MRD and high SDRD in the group 4 (orange line), the three-cluster analysis failed to identify this meaningful group.

reservoir in remediating extreme events and unexpected water crisis (Shah, 2009). The recent water crisis in Cape Town, Africa is one of the examples (Nel et al., 2018; Nordling, 2018). Under an emerging need for groundwater use, our study has provided an opportunity to have a targeted management strategy based on the spatio-temporal information of groundwater. Further studies could investigate the local groundwater use and its impacts to stakeholders' livelihoods which may help to develop a community-based strategy for the sustainable use of groundwater resource.

5. Conclusions

This study provides a holistic analysis on spatial-temporal dynamics of groundwater resource in the YRB. The middle reach of the YRB (north of Ningxia and west of Neimengu) displays the most time stable characteristics in terms of the groundwater changes, therefore can be used as a representative monitoring area to show the overall changes of the YRB overtime. Moreover, the origin of the Yellow River and its river mouth showed severe groundwater falls and high fluctuations which displayed two extreme cases respectively devastated by natural and human pressures. We suggested robust risk response systems should be installed in these two regions and more serious regulations on groundwater use should be implemented in the Yellow River Delta. The cautions and efforts put on groundwater management will not only help to satisfy the long-term needs of residents on portable water and food, but also help to strengthen the region's resilience in facing the threat of climate change and growing populations. The method of time stability analysis coupled with multivariate cluster analysis is promising to be adopted to other groundwater-fed regions to build a more effective and sustainable management system for groundwater resource.

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